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Changing Sunshine: Analyzing the dynamics of solar electricity policies in the global context

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ABSTRACT

Although solar costs have been dropping in recent years, solar power is still more expensive than conventional and other renewable energy options, and in most applications solar power still needs continuing government policy support. However, the need to achieve multiple objectives and ensure sufficient political support for solar power makes it difficult for policy makers to design an optimal solar power policy. The dynamic and uncertain nature of the solar industry, combined with the constraints imposed by broader economic, political and social conditions further complicates the task of policy making. In this paper, we present a framework to critically analyze the objectives behind different country policies, how factors such as macro-economic conditions and development paradigms affect the policy outcomes and finally, how these outcomes affect the overall cost reduction of solar energy. We find that while the extent of cost reduction through creation of large demand remains to be seen, it is essential for governments to provide adequate support for leapfrog RD&D, and exploit real comparative advantages across countries for effective solar cost reduction. Policy makers need to optimally design their policies by balancing national objectives and paying capacity with the global objective of solar power cost reduction in order to realize its full potential.

Contents

1. Introduction

Solar power has tremendous potential in terms of resource availability, and its costs have been dropping over the years. However,

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it is still relatively expensive compared to conventional as well as other renewable energy (RE) generation options. Rapid cost reduction of solar electricity to achieve grid parity is the global societal goal, since this will facilitate widespread deployment of solar. However, in this paper, we show that government policies are driven by objectives that go beyond the goal of achieving grid parity. These policies may be formulated to increase renewable energy generation to mitigate climate change, or boost energy security; develop domestic industry to create jobs and exports; develop technology and intellectual property rights via R&D; and/or improve access to electricity where the electric grid is unreliable or absent.

The need to achieve multiple objectives and ensure sufficient political support for solar power makes it difficult for policy makers to design the optimal solar power policy. The dynamic and uncertain nature of the solar industry (e.g. cost of technology, efficiency, introduction of new technologies, etc.) complicates the task of policy making even further. In addition, policy makers are constrained by broader economic, political and social conditions (e.g. the 2008 economic crisis that forced many governments to adopt austerity measures, thereby reducing their appetite for continuing extensive subsidies for purposes such as solar development). Finally, the lessons learnt during the relatively short history of the solar sector offer limited insights for the selection of policies.

Several reports track the progress of the solar industry and the policies and incentives offered by various governments [1–4]. Some papers have described the various solar policies and recent progress in different countries [5–7]. In our paper, we present a framework to critically analyze the objectives behind different country policies, how factors such as macro-economic conditions and development paradigms affect the policy outcomes and finally, how these outcomes affect the overall cost reduction of solar energy. Some authors have analyzed solar cost reductions by applying learning curves theory [8,9]. However, other studies have gone beyond the learning curves and have analyzed the different factors that may be responsible for the overall cost reductions [10]. Further, some studies have discussed the role of different types of policies in inducing cost reductions [11,12]. We have build upon these latter studies to assess the factors responsible for cost reduction by providing anecdotal evidence from recent developments and outcomes in the solar sector, and connecting them back to different country policies and objectives.

We analyze the solar promotion policies of seven countries—Germany, Spain, the United States, Japan, China, Taiwan, and India—which provide key insights in terms of their objectives, policy mechanisms and outcomes. Germany has been a leader in solar photovoltaic (PV) installed capacity since the middle of the 2000s, and is also a leading exporter of solar technologies. Spain's experience is useful due to its meteoric rise in installed solar PV capacity spurred by generous government support, followed by a bust due to a drastic reduction in that support. However, the nation continues to strongly support its concentrated solar power (CSP) industry and, with the US, is a leader in the industry.

The US has been a leader in both manufacturing and deployment of both solar PV and CSP. Although policies to support solar power vary substantially across states in the US, deployment is significant in California as a result of its ambitious goals for renewable energy production and carbon emission reductions. Japan has been the world leader in solar PV manufacturing and exports as well as installed capacity during the first half of the 2000s. China has the largest PV cell manufacturing capacity in the world, with Taiwan being the second largest manufacturer. Both these countries have focused on exports of solar equipment to markets such as the EU and US, and until recently, have not provided any significant purchase support to increase installed capacity at home. Finally, India is a new entrant, both in terms of manufacturing and pursuing deployment under its National Solar Mission and various other state initiatives.

We attempt to draw out key lessons in primarily qualitative terms, regarding the effectiveness of the policies to achieve the stated objectives of these countries, and how their outcomes affect overall solar cost reduction. We provide insights for policy makers to optimally design their solar policies by balancing national objectives and paying capacity with the global objective of solar power cost reduction.

2. Framework and methodology

A summary of the underlying framework used in our analysis is shown in Fig. 1. We begin by reviewing the key policy objectives adopted by various countries. We then present the different policy mechanisms that are being adopted by governments to fulfill their

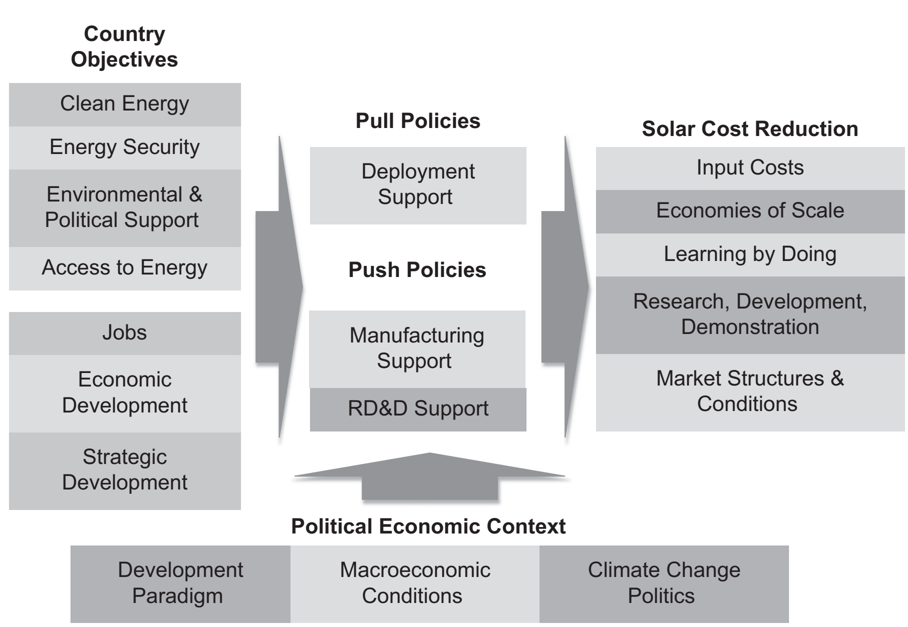

Fig. 1. Framework for assessing the effectiveness of solar policies.

objectives. Subsequently, we discuss the political-economic contexts that have influenced policies of individual countries. Finally, we study the outcomes of the policies and their impact on lowering the global cost of solar power through five different cost reduction mechanisms.

2.1. Country objectives

Cost reduction of solar is the global societal objective, which would enable solar power to penetrate a large part of the market without needing additional financial or other support to make it financially viable. Statements by several jurisdictions formally acknowledge cost reduction as the broader objective of their solar power policies, in line with the ultimate objective of the global solar sector. Examples include Germany's Renewable Energy Sources Act [13], California's Senate Bill 1 [14] and India's National Solar Mission [15].

On one hand, due to the global nature of both the market and the supply chain of solar power, it is less likely that the policies of just one nation or region would unilaterally achieve the required cost reduction. On the other hand, domestic politics usually requires governments to highlight other objectives in order to build and develop political support for solar policies. This is especially important since the political appetite for providing massive ongoing subsidies for solar power within a country, especially in the current economic slowdown, can be limited. Consequently, policy makers have to choose the most effective of various levers to achieve maximum cost reduction, while also maintaining political support. Most policy makers have aggressively sought political support for their solar policies by highlighting both clean deployment and domestic value addition as key objectives.

We have identified four distinct clean deployment objectives. (a) Increasing the contribution of clean energy to mitigate carbon emissions and other pollution is an objective stated across all policy documents that support solar deployment. (b) Enhancing energy security by reducing dependence on current or potential future imports of fuel for energy production is also a commonly stated objective especially for those countries that rely on fuel imports for electricity generation such as Japan [16], Spain [17], and Germany [18], the latter especially after its resolve to phase out nuclear power. (c) Creating political symbols such as rooftop PV installations, which provide visible evidence of a society cherishing environment friendly values, and thus sustaining political support for environmental policies is not an overtly stated objective, but is evident from the greater support for rooftop PV [2] in the form of higher compensation compared to large solar plants that may be less visible to society. (d) Finally, ensuring access to energy for customers in underserved regions through decentralized and off-grid applications is an important objective for countries such as India striving to provide quick access to clean lighting in the absence of an electric grid [15].

Domestic value addition objectives consist of (a) job creation, (b) economic development or increasing GDP, and (c) strategic development. While employment trends in the solar industry are imprecisely understood, growth in jobs has been visible [19,20]. Broader economic development is also likely to result from supporting the solar sector. This is an indirect benefit of manufacturing and/or installation, and results from the creation of ancillary industries to support sector growth in tax revenues, human resource capability, infrastructure investments, etc. The third broader objective in domestic value addition is strategic, i.e. supporting innovation, research and technology development, and creation of intellectual property rights to improve the positioning and competitiveness of domestic industries on world markets [21].

2.2. Policies

Policies used to support solar energy across the world are typically classified into two categories—demand-pull and technology-push [11,12]. In general, most jurisdictions prefer some combination of push and pull policies.

'Pull' policies are intended to stimulate demand. Feed-in Tariff (FiT), a generation-based incentive, is by far the most popular pull policy, with more than 60 countries having adopted solar-specific FiTs by the end of 2011 [4]. The other popular pull policy is the Renewable Purchase Obligation (RPO) or Renewable Portfolio Standard (RPS). A RPO/RPS is a legislated quota obligation or a binding renewable energy target which requires that a minimum percentage of electricity generation installed capacity or electricity generated or sold be provided by renewable energy. RPO/RPS policies have been enacted at the national level in over 10 countries and in at least 50 jurisdictions, including 30 U.S. states [4]. Renewable Energy Certificates (REC)—environmental or green credits of renewable electricity that can be traded to meet renewable energy targets—can work in tandem with an RPO/RPS policy. Several European countries, Australia, Japan, India and others have REC markets [4].

Other pull policy mechanisms include capital-based (i.e. per watt of installed capacity) incentives or rebates, tax incentives (investment tax credits and production tax credits), grants, interest subsidies or low-cost financing, and loan guarantees. Most of these and other forms of subsidies are financed from either electricity ratepayer charges and/or taxpayers monies.

'Push' policies support the creation of businesses in the solar supply chain, especially, those that manufacture solar power components and systems. This support is usually in the form of grants or low-cost loans, tax concessions, RD&D grants, training activities, and the provision of reliable and often, subsidized support infrastructure (e.g. land, energy, water, communications, and transportation). Policy makers also support the development of capacity-creating networks/clusters for industry. Such supplemental support can lower some of the non-monetary barriers that can impede the growth of the solar sector, including lack of skilled personnel and research facilities, inadequate means of information sharing, and inadequate infrastructure for pilot projects and development.

2.3. Political-economic context

Global and national macroeconomic conditions impact the level and duration of solar support policies significantly. The main financial support provided for solar power consists of ratepayer funds (i.e. those collected from electricity customers through a surcharge on their bills) and taxpayer funds allocated from government budgets. Local economic conditions—recession, unemployment, budget and trade deficits, and competing social and political priorities—have a strong influence on both the level of support and its long-term sustainability.

According to the International Monetary Fund's September 2011 World Economic Outlook [22], emerging economies such as China and India are making a rapid recovery since the economic crisis of 2008, but many of the advanced economies are not. There are concerns regarding the ability of many European countries as well as the United States to stabilize their public debt. As most of the large investments in solar deployment over the last decade had been committed to in the advanced economies (especially Germany, Spain, Italy, Czech Republic and parts of the US), governments there have been forced to reconsider their generous

support for solar in light of their respective macroeconomic priorities (e.g. debt reduction).

The economic development paradigm also affects the nature and extent of the support for solar. Since the end of the Second World War, the US, Germany and Japan have invested heavily in the development of advanced technologies and manufacturing. Unlike the US, both Germany and Japan focused substantially on increasing their exports, especially to markets such as the US. Starting substantially later, the four Asian Tigers (Taiwan, Korea, Singapore, and Hong Kong) and then China developed their own export-oriented growth models [23,24]. Each of these countries has also systematically shifted to the manufacturing of higher value-added products. This economic development paradigm is reflected in the positive current account balances of countries following the export-oriented growth model [25].

Finally, international and local climate change politics affect solar policies and their outcomes. Efforts to establish a new global climate change mitigation treaty have so far failed, as was evident from the Copenhagen and Cancun Conferences of the Parties in 2009 and 2010 respectively [26]. However, the individual jurisdiction environmental protection regimes (especially climate change mitigation) are a crucial driver for supporting policies targeting renewables. While international negotiations continue, several major GHG emitters including Germany, United States, China and India have initiated programs to support solar, both to show their willingness to take up some responsibility for mitigation, and to grow a business sector that might capture future exports.

2.4. *Solar cost reduction factors*

Most cost reduction theories present learning curves, a black box approach that tries to explain cost reductions observed over time for many technologies by quantifying the cost reduction (or some other characteristic of the technology such as efficiency) achieved in relation to the level of experience with that technology (e.g. production or installed capacity) [9,27,28]. However, some researchers such as Nemet find that learning-by-doing as defined in the learning curves theory only weakly explains the cost reductions achieved in solar PV [10]. Nemet has explored several factors that affect solar cost reductions, which we draw upon.

In this study, we have broken down cost reduction into five mechanisms in order to analyze which policies are likely to affect which mechanism. These include costs of inputs, learning-by-doing, economies-of-scale, RD&D, and market structure. These mechanisms do not necessarily operate independently of each other.

The key inputs in the production of solar power include basic materials such as silicon for PV cells, steel, and glass, land, utility infrastructure, labor, capital, and intellectual property. Substitution of cheaper inputs for more expensive inputs (e.g. automation of product lines to reduce labor costs), use of lesser quantity of inputs (e.g. reducing wastage of materials, etc.), and more efficient processes throughout the solar power value chain can contribute to the cost reduction objective [10]. Other factors that influence the cost of inputs are geographic distribution of source of inputs, geographic variability in cost of inputs and market supply and demand.

The effect of economies-of-scale, both due to increase in installation sizes and manufacturing capacities can significantly reduce the average per unit costs of solar. Learning-by-doing refers to improvements in performance, efficiency, costs, etc. achieved as a worker or business gains experience that enhances expertise and reduces errors [10]. Costs tend to drop as manufacturers gain more experience in producing certain products. ‘Cross-learning’ between firms making different products can also lower costs. This effect has been seen in the PV sector between semiconductor and Si-based solar PV industries, and between thin film transistor liquid crystal display (TFT-LCD) and thin film PV industries [29].

RD&D activities leading to both incremental and non-incremental or ‘leapfrog’ improvements are crucial for reducing costs. Leapfrog RD&D consists of discovering or inventing fundamentally new materials, processes, or techniques that can create a radically better technology by raising its efficiencies and/or lowering its costs of production. For example, CdTe thin film, which competes with crystalline Si PV, promises lower costs as a result of leapfrog RD&D. Knowledge spillover externalities may lead to under-investment in RD&D by the private sector and push policies may be important for leapfrog change in technology [11].

Finally, from the perspective of achieving rapid cost reductions, the market structure should ideally have attributes including but not limited to the ability to deploy resources optimally across the world, competitiveness, the ability to sustain business models over a long term, the ability to incentivize innovations, minimal transaction costs, and the ability to effectively manage risks. Competition leads to reduction in margins and lower prices, and a price-based experience curve may over-estimate the rate of technical progress or reduction in actual costs [10].

3. Objectives and outcomes of policies

In this section, we assess the outcomes of solar policies in meeting different country objectives. We employ various metrics wherever possible as well as provide relevant anecdotal examples to assess the effectiveness of these solar policies.

a) Most pull policies for increasing solar deployment state clean energy generation and energy security as objectives. Spain, Japan, and Taiwan, on one hand, rely significantly on imports for the energy used for electricity generation. On the other hand, China, the US, India, and Germany (the world’s top four coal consumers) use mostly domestically produced coal to generate electricity [30]. The eventual dwindling of coal reserves and, more importantly, the growing public opposition to coal and other fossil fuel-based electricity generation due to local and global pollution, has made clean energy a major objective of energy policy in these countries. However, as shown in Fig. 2, the share of solar energy generation in different electricity sectors is very small. Further, it is likely to continue to be small in the near future [31]. Even considering a high 50 percent year-on-year growth for solar PV installations, the contribution of solar PV to the overall electricity mix will be well below 5 percent over the next five years. Until solar costs drop, countries may prefer investing significantly more in other lower cost renewables, such as wind, hydro and biomass, to meet their objective of achieving higher clean energy penetration and ensuring energy security. In other words, the contribution of solar power deployment to achieve those national objectives may remain small in the near future. However, the contribution of solar power to the overall energy mix may become significant in a small number of countries such as Germany that continue to provide large long term subsidies. At the current growth rate of solar installations, Germany is likely to procure over 10 percent of its electricity generation from solar by 2020 [32], an important contribution from an energy security perspective given Germany’s decision to phase out nuclear power by 2022.
b) Utility-scale solar PV plants are in most cases the least expensive option for PV deployment, due to economies of scale and their potential location in high solar resource areas, which more than offset the losses due to transmission to load areas. However, most countries explicitly promote distributed applications, both grid-connected and off-grid, rather than utility-scale plants. Fig. 3 shows that with the exception of

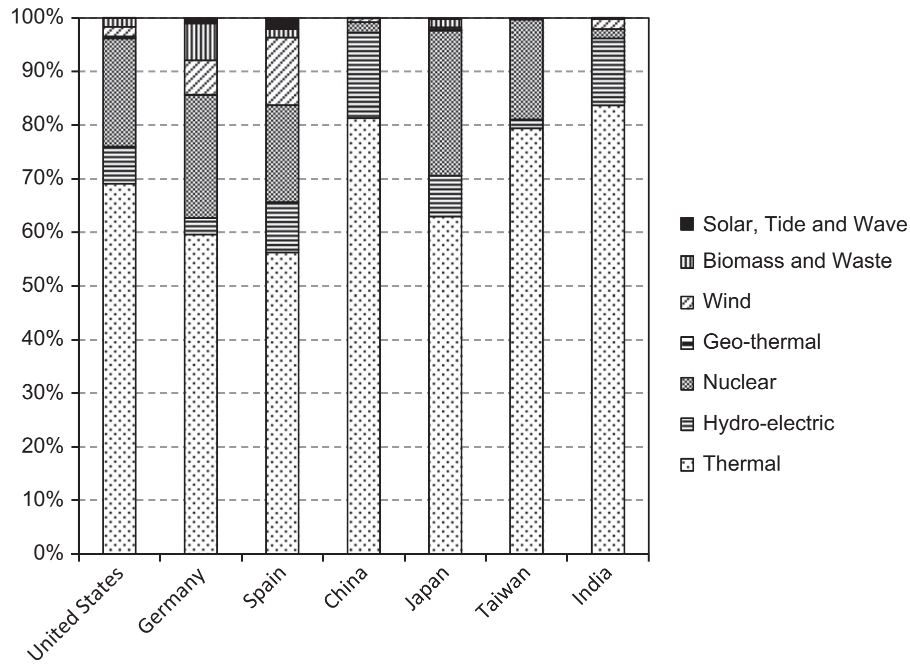

Fig. 2. Electricity generation by source in 2009 [30].

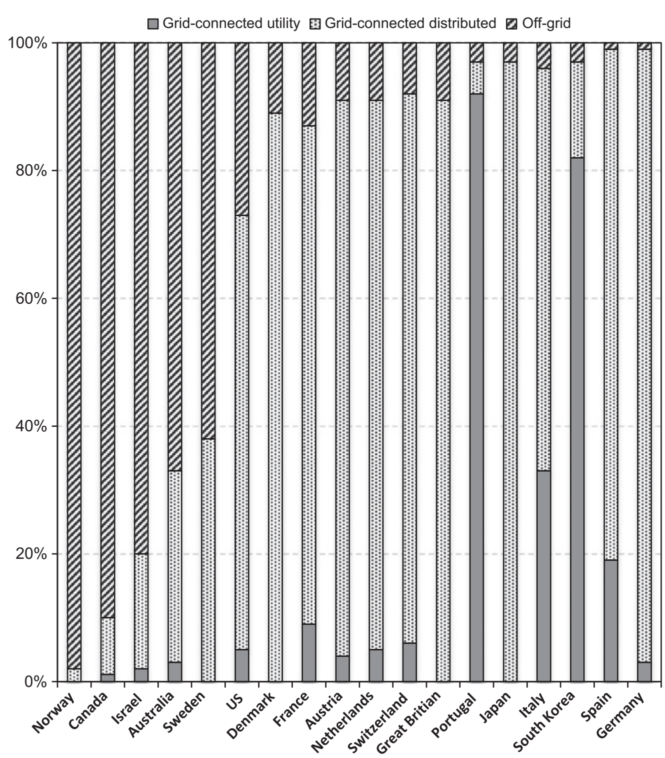

Fig. 3. Application market share of cumulative installed PV capacity in IEA countries through 2008 [33].

Portugal and Spain, majority of the solar deployment has not been utility scale grid connected solar [33]. Most countries offer much higher generation tariffs for smaller-sized distributed and rooftop systems [3]. Until recently, China was concentrating primarily on off-grid solar PV deployment through its Brightness Rural Electrification Program (started in 1998) and the Township Electrification Program (Song Dian Sao Xiang Program started in 2002) to provide energy to its remote communities [34]. Similarly, India offers subsidies for off-grid solar applications, especially to provide lighting [35]. The objectives of achieving increasing public awareness and supporting 'green' movements as well as increasing access to electricity and clean lighting for the under-served population play a strong role in national solar deployment policies.

c) In terms of domestic value addition, jobs creation is one of the main objectives for providing policy support. According to New Energy Finance, in 2008, the solar electric industry was responsible for 173,000 direct and indirect job-years. Of this total, approximately 169,000 were accounted by the PV sector, and about 4000 by CSP [36]. Another study by the United Nations Environment Programme for the year 2007 estimated 170,000 global PV jobs, with China accounting for the highest (55,000), followed by Germany and Japan (both about 35,000) and Spain (26,000) [19]. Pull policies directly create jobs in the installation sector, while push policies directly create jobs in the manufacturing and RD&D sectors.
d) Broader economic development is likely to result from supporting the solar sector especially using push policies but also pull policies. If exports were to be considered a parameter to assess economic activity, the top four exporters and their shares in 2009 were China (41.2%), Japan (18%), Germany (17.5%) and the US (9.3%) [37]. The US has been a significant net exporter of solar energy products, with total net exports of US$1.9 billion in 2010 [38]. Both China and Taiwan have relied mainly on exports to develop their manufacturing capacity without providing any significant deployment support although China has recently begun to provide some deployment support given falling PV prices [39].
e) Pull policies alone may not lead to economic development through industry growth, since they may result in imports of lower cost solar equipment from already developed industries in other countries. Such an outcome may result in loss of political support for those pull policies. To develop and support their domestic industry, countries may use push policies or opt to mandate domestic content in their pull policies. Examples are India's mandates under its National Solar Mission, Ontario's Microfit program and the United States' domestic content requirements for solar projects funded under the American Recovery and

Reinvestment Act [40–42]. Although such policies may lead to higher deployment costs in the short term due to the infancy of the domestic industry, lack of exposure to international competition and other potential comparative disadvantages, these may lead to the development of the domestic industry and realize potential cost reductions for the global industry in the future. In their study of the wind industry, Lewis and Wiser found a positive correlation between a manufacturer's success in its home country and its eventual success in the global wind power market. Further the success of the new entrants was found to be dependent in part on the utilization of their turbines in their domestic market [43]. They conclude that policies that support a sizable stable market for wind power, in conjunction with policies that specifically provide incentives for wind power technology to be manufactured locally, are most likely to result in the establishment of an internationally competitive wind industry. China and Spain's domestic content mandates for their wind deployment played a role in the rise of their respective domestic industries [43]. However, countries with established industries may oppose such moves, as illustrated by Japan's trade dispute with Canada (Province of Ontario) at the World Trade Organization, and concerns raised by the United States Trade Representative regarding India's domestic content requirements [44,45].

f) Several countries have a long history of supporting their industries including solar through push policies by providing incentives, which may effectively lower their costs of inputs. Germany provides incentives like low interest loans and tax credits to solar manufacturing industries to set up facilities in former East German provinces [46]. The US provides loan guarantees and other incentives to its renewable energy industry [47]. China's currency policy of pegging the yuan to the US dollar arguably has an effect on making China's exports more competitive, as does low-interest finance from state-owned banks [48]. However, the present economic slowdown has led to a tussle between nations to secure the financial and employment gains associated with developing the clean energy industry. For example, in September 2010, the 850,000-member United Steelworkers Union, a US labor union, filed a trade case accusing China of violating the World Trade Organization's free trade rules by subsidizing exports of clean energy equipment like solar panels and wind turbines [49].

g) Push policy support for RD&D creates intellectual property rights in a future growth industry so that domestic firms might steadily rise through the value chain of products. Countries like Japan, the US and Germany have traditionally invested in RD&D, which is reflected in the number of their patent applications in the field of solar energy as seen in Fig. 4 [50].

In general, profit margins for most products are higher at the two ends of the supply chain—RD&D/brand design and sales/marketing. The middle portion of the supply chain-manufacturing—typically accrues the lowest profit margins per unit. Chinese industries have initially focused on manufacturing, while US companies that outsourced manufacturing to China controlled the RD&D/brand design and retail sales. Consequently, the US operations enjoyed the highest profit margins, while the Chinese firms had the lowest. However, in recent years, Chinese firms have developed their own brands e.g. three Chinese companies are amongst the top ten global solar PV cell and module manufacturers [51]. The Chinese government has significantly increased RD&D support for energy technologies such as hydrogen fuel cells, energy efficiency, clean coal, and renewable energy under the National High-Tech Development Plan (863 program) and the National Basic Research Program (973 program) [52].

h) Macro-economic conditions can severely affect the outcome and course of solar policies. The total burden of existing commitments to solar PV undertaken by the German electricity ratepayers up to 2009 was approximately €52 billion (2007 euros) [53]. The financial crisis and falling solar costs resulted in Germany slashing its solar FiTs twice during 2010, with more cuts planned for 2011. Nonetheless, Germany installed more than 7 GW of PV in 2010 [1]. However, the story was different in Spain. In 2008, Spain became the leading installer of PV after Royal Decree 661/2007 substantially increased FiTs for PV. However, the annual installed capacity of 2.7 GW significantly exceeded the annual cap of 1.2 GW, mainly due to Spain's policy of accepting projects until one year after 85 percent of the cap was achieved. This additional subsidy commitment became a burden on the government exchequer especially since the Spanish government has kept the electricity consumer tariffs low and has been reimbursing utilities from the national budget for the deficit. When Spain was one of the worst-hit countries during the financial crisis, Royal Decree 1578, issued in September 2008, slashed the FiTs and introduced a provision requiring that two-thirds of the capacity should be rooftop-mounted and allowed no free-field systems. The Spanish PV market crashed with less than 20 MW installed in 2009 [54]. The trends in both annual installed capacity and FiT changes since 2006 are shown in Fig. 5. The solar market in the Czech Republic also crashed after a dramatic growth driven by an overly generous FiT scheme followed by a moratorium on new plants and a 26% retroactive tax on benefits generated by large PV plants [1].

4. Effect of policies on solar cost reduction

Cost reduction is acknowledged as the broader objective of the solar power policy statements of several jurisdictions. However, policies of individual countries cater to their own specific objectives and are influenced by political-economic factors. Hence, although each of these policies and their implementation mechanisms has reduced solar power costs, they have done so with varying degrees of effectiveness. While studies such as Nemet's [10] quantify factors beyond the learning curve that affect solar PV cost reduction,

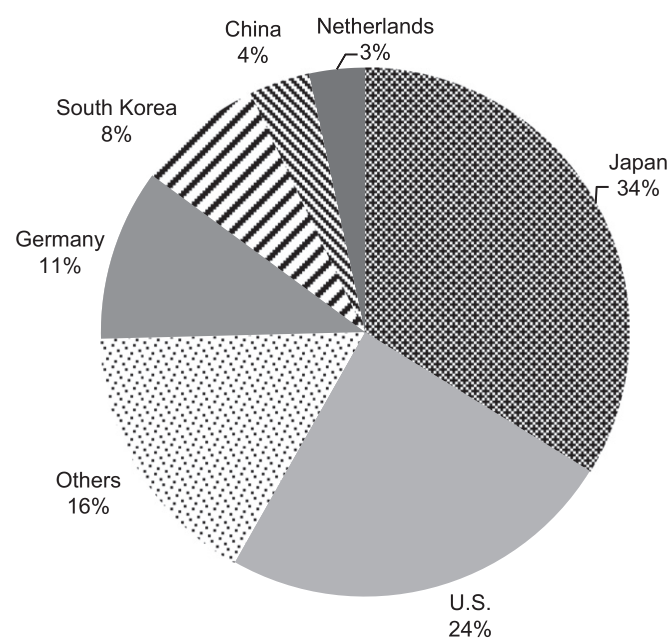

Fig. 4. Country share of patent applications in the field of solar energy from 2005 to 2009 [50].

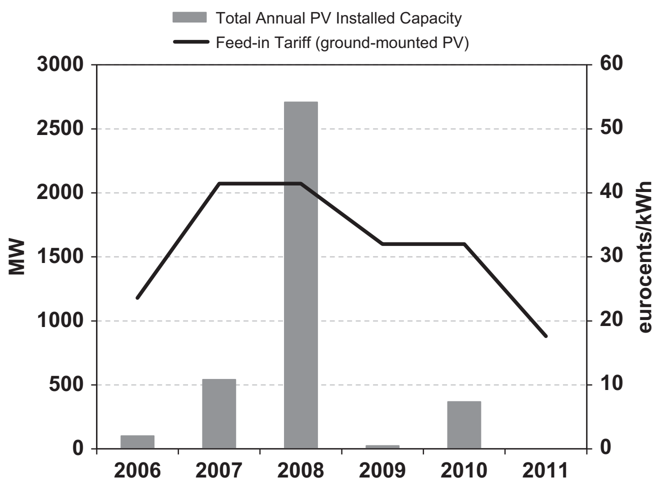

Fig. 5. Spain's annual solar PV installed capacity and feed-in tariffs [1,3]. *Note:* Annual Installed capacity includes all PV installations. Feed-in tariffs for only ground-mounted PV systems shown.

updated data to reflect recent improvements will assist in drawing definitive conclusions. Here, we have attempted to qualitatively assess the factors that have affected solar PV cost reductions.

Pull policies directly influence two cost reduction mechanisms—economies-of-scale and learning-by-doing. Depending on their scope and long-term sustainability, pull policies may also indirectly affect input prices (due to large-scale production), incentivize RD&D (mainly among firms that invest in RD&D to remain competitive), and impact market structure (fragmented small players versus large companies). Manufacturing support directly affects costs of inputs, economies-of-scale, learning-by-doing and market structure, but has limited or no effect on RD&D. Similarly, RD&D support directly affects costs of inputs and RD&D, but has limited or no effect on economies-of-scale, learning-by-doing and market structure.

Fig. 6 shows the trends in the average module price for PV and the global cumulative installed capacities [1,55]. We present the key observations from these trends.

a) There was a large price reduction from the early 1980s through the early 2000s, mainly as a result of sustained RD&D in developed countries such as Germany, Japan and the US [33].
b) The interest of policy makers to target substantial capacity additions arose only in 2000 after the price had decreased significantly. The growth in cumulative installed capacity began in the early 2000s, with rapid acceleration taking place in the late 2000s (Fig. 6).
c) In barely one decade (1999–2010), solar PV capacity grew from a modest total of less than 0.5 GW to approximately 40 GW—approximately a hundred-fold increase (Fig. 6). Over the same decade, the average module price at the factory gate (in real dollars) was more or less steady at approximately US$4/watt till 2007 and the cost reductions were not as significant as those achieved during the 1980–1999 period [33,54] for several reasons including a silicon supply constraint.
d) However, the price saw a decrease since 2008 when more than 75 percent of the cumulative PV capacity till 2010 was installed. Many studies attribute the cost reduction of solar power to "learning curves" or "economies of scale" effect in terms of increasing global PV demand. However, it is unclear to what extent the role of demand or pull policies have had on the overall cost reduction of solar as opposed to factors such as RD&D investment and other push policies.
e) As a result of poor macroeconomic conditions, especially in OECD countries, some governments such as Spain and Czech Republic have curtailed their generous support for solar since 2008, while others are reducing their feed-in tariffs to limit installations. At the same time, supply has ramped up substantially, which has resulted in a demand-driven market with a manufacturing overcapacity. Hence, although demand has been growing, the over-supply situation has driven prices down [56].

There is no doubt that costs have decreased through reducing costs of inputs, economies-of-scale, learning-by-doing, RD&D and market structure or competition. However, policy makers need to assess the relative contributions of each of these mechanisms to determine how best to achieve further cost reductions. We highlight some of the trends in the underlying cost reduction mechanisms that may have contributed to the overall trends shown in Fig. 6, and the policies that may have contributed towards them.

4.1. Inputs

a) Until 2006, Japan and Germany dominated solar PV cells manufacturing (Fig. 7). However, push policies adopted by China and Taiwan providing manufacturing support shifted a huge share of PV cell and module production from Japan and Germany to China and Taiwan. This shift in PV cell production was due to the comparative advantage that China and Taiwan enjoy in terms of access to capital and lower capital and land costs, in addition to other incentives [57]. Similarly, PV module production has moved to Asian countries, mainly China, to take advantage of the low labor costs. Comparative advantages can reduce input costs.
b) As mentioned in the earlier section, support from governments for the solar industry subsidizes the costs of their inputs. Interest subsidies that reduce the cost of capital, land allotment, subsidized utility services and currency policies, all play a role in reducing the costs of inputs for the industry. Although these subsidies are by themselves not real cost reductions, they may eventually reduce the costs of solar by establishing a competitive global industry and encouraging its development.
c) Although not a factor in the actual cost of the solar equipment or installation, the quality of solar resource directly affects the levelized cost of solar energy generation. Higher levelized cost of energy leads to either more subsidies or less demand. This is especially important for the solar PV market, since more than 50 percent of the global installed capacity till 2010 has been in two countries with relatively poor solar resource—Germany (17.2 GW) and Japan (3.6 GW) (Fig. 8). Because both Germany and Japan have a poor solar resource (significantly less than in Spain, Italy, India or North African countries) [59], PV systems in these countries generate significantly less amount of electricity as compared to that in sunny countries, leading to greater levelized cost of generation.

4.2. Economies-of-scale

a) In terms of manufacturing economies-of-scale, many leading firms have already achieved 1 GW-plus manufacturing capability at the plant level [51]. Consequently, the future incremental potential to reduce production costs through economies-of-scale in manufacturing remains to be seen.
b) At the project deployment scale, the least-cost option for solar PV deployment is free-field installations, which have the advantage of economies-of-scale. However, most countries encourage smaller scale PV plants by offering higher feed-in tariffs compared to free-field installations, thereby forgoing any cost reductions from

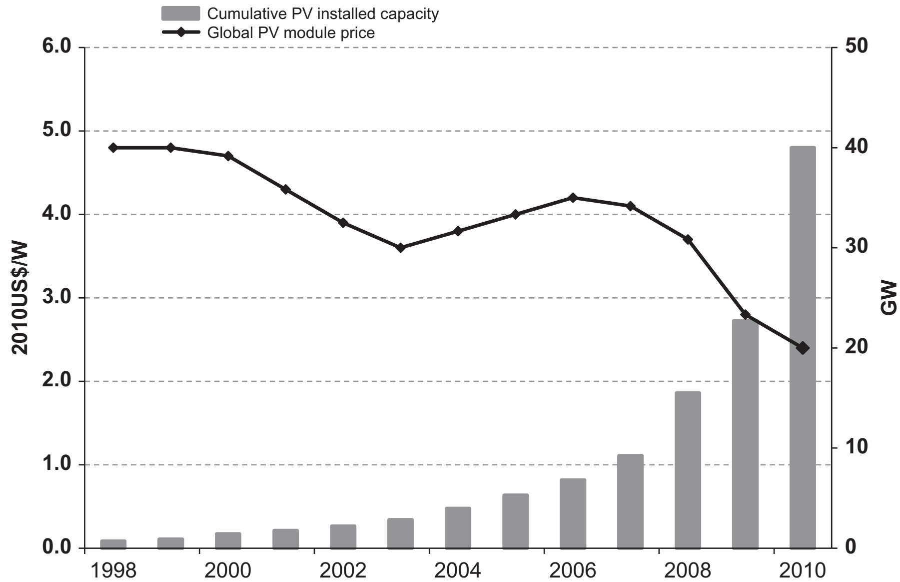

Fig. 6. Solar PV module prices and cumulative installed capacity from 1998 to 2010 [1,55].

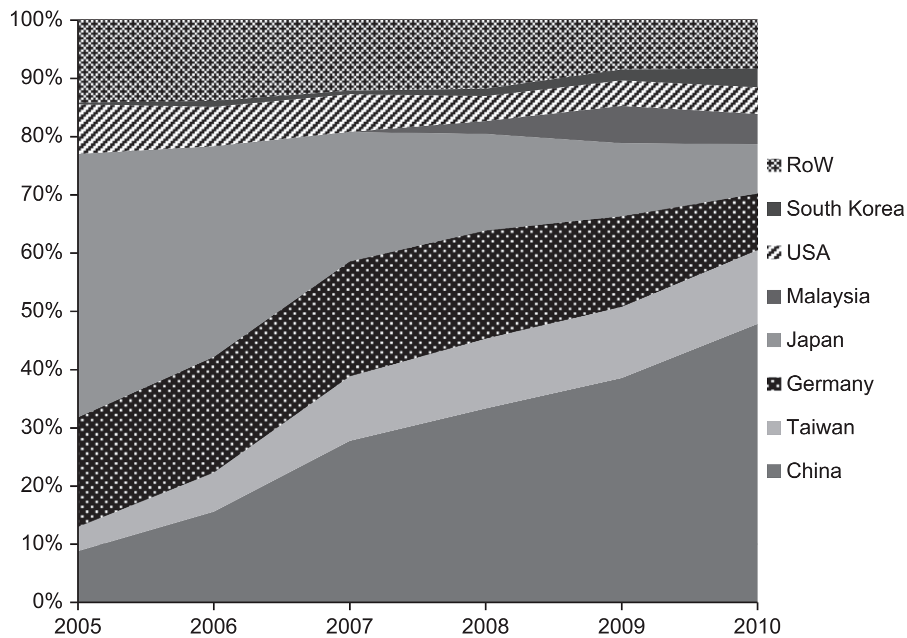

Fig. 7. Country share of solar PV cell production [58].

economies-of-scale. For example, more than 99 percent of Germany's PV installations from January 2009 to August 2010, accounting for 85 percent of the 8.7 GW installed capacity during that period, were less than 1 MW in size (Fig. 9).

4.3. Learning-by-doing

a) Average installed cost of 2–5 kW residential PV installations in 2010 (excluding sales/value added tax) was significantly lower in Germany (US$4.2/W) than in Japan (US$6.4/W) and the US (US$6.9/W) [55]. Some of these cost reductions may be partly attributed to the learning-by-doing phenomenon, brought about by a significantly greater number of installations in Germany compared to Japan and the U.S. However, the role of several factors including different incentive levels, module prices, labor costs, permitting, average system size, etc. need to be studied to draw definitive conclusions [55].
b) Learning across industries can be important for cost reduction. Countries like Taiwan, Germany and China got an edge in the international PV market by developing industry clusters for learning across such industries as semiconductors and flat displays (TFT-LCD) [29,46].

4.4. Research development & demonstration

a) Incremental RD&D, especially that pursued by industries to improve their technology and processes in order to remain competitive, has been responsible for improving efficiency and reducing costs. Some examples are RD&D to reduce the amount of material and energy inputs, as well as improving

efficiencies of the solar modules while lowering costs [61]. Various solar PV technologies have steadily improved, with efficiencies of mono-crystalline cells (which account for more than 90 percent of cumulative installed capacity) rising from approximately 14 percent to more than 19 percent (Fig. 10). However, large cost reductions needed for solar power to be competitive without subsidies are unlikely to be achieved with technologies that are presently in widespread production [62].

b) Breakthrough or non-incremental RD&D has a large potential to leapfrog existing technologies and ultimately bring about major reductions in costs of solar power. For example, Cadmium Telluride (CdTe) thin film technology lowered solar PV module costs enough to pose a big challenge to the dominant crystalline-Si technology, and First Solar (the company promoting CdTe) has one of the largest PV market shares [51]. Several leapfrog technologies such as Copper Indium Gallium Selenide (CIGS), Concentrated Photovoltaic (CPV) with multi-junction cells, and others are in various phases of development. Technology push support is able to incentivize non-incremental RD&D [12].

c) Usually, the industry is likely to invest in technologies that can be commercialized in 2–4 years, and focus on those opportunities through incremental improvements that increase their profitability and market share [62]. Further, the focus on pull or deployment policies may only foster incremental innovation and in some cases, even disincentivize non-incremental innovation, both due to uncertainty associated with RD&D returns, as well as spillover effects [12]. Hence, government investment and support for RD&D is essential, both for basic research and pre-commercial technologies as well as sending signals to the market [61,63].

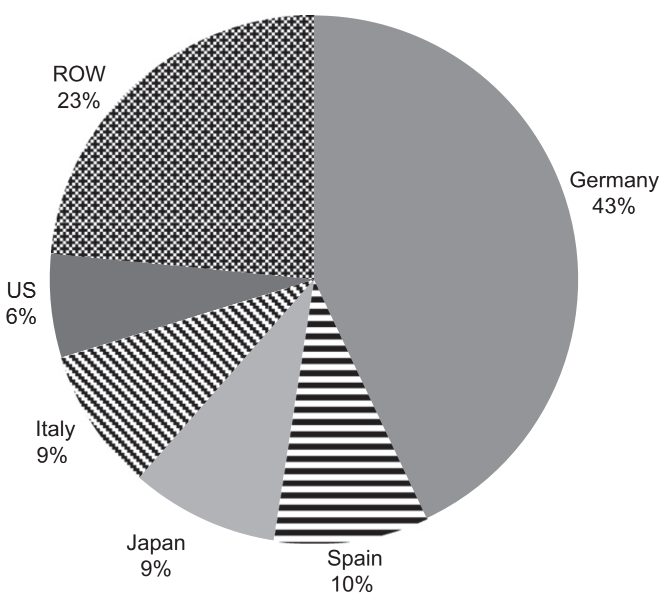

Fig. 8. Country share of cumulative PV installed capacity in 2010 [1].

4.5. Market structure

a) Market structure plays a critical role in reducing the price, as well as cost of products. The prices of inputs such as polysilicon, silicon, steel, and glass depend on the status of their demand and supply. For example the silicon industry was historically dominated by a few firms from the U.S., Germany and Japan. Increasing demand for PV led to a shortage of polysilicon in 2005–2008. However, massive investments in new capacities especially in China led to an oversupply in 2009, sending the spot price down from its maximum of US$500 per kg to approximately US$55 per kg [57,64].

b) Increased reliance on solar technologies such as thin films has increased the reliance on specific metals mined in only a few geographic locations. China controls approximately 97 percent of the world's 'rare earth' market [65]. Because of diplomatic tensions between China and Japan over a security incident in 2010, the Chinese government blocked the exports of some of these 'rare earth' minerals to Japan [66]. Individual countries or regions can thus exploit monopolies based on strategic considerations, in this case by restricting the export of 'rare earth' materials to the global market, thereby distorting the supply–demand equilibrium and artificially raising their costs.

c) In an over-supply market scenario, the ongoing commoditization of solar PV technology components—especially, for the mature and dominant c-Si technology—combined with existence of hundreds of manufacturers, has exerted substantial downward pressure on the profit margins of all the manufacturers. Consequently, the industry as a whole is less likely to invest in RD&D beyond the existing trajectory and dominant designs in production [12]. In other words, industry is more likely to invest in manufacturing activities and incremental RD&D to bolster their market share. This makes government support and push policies essential to pursue non-incremental RD&D opportunities, which have high risk but also have high return on investment in terms of cost reduction. However, according to a 2010 report of the International Energy Agency, the global budget for RD&D was US$680 million/year, which is a fraction of the subsidy

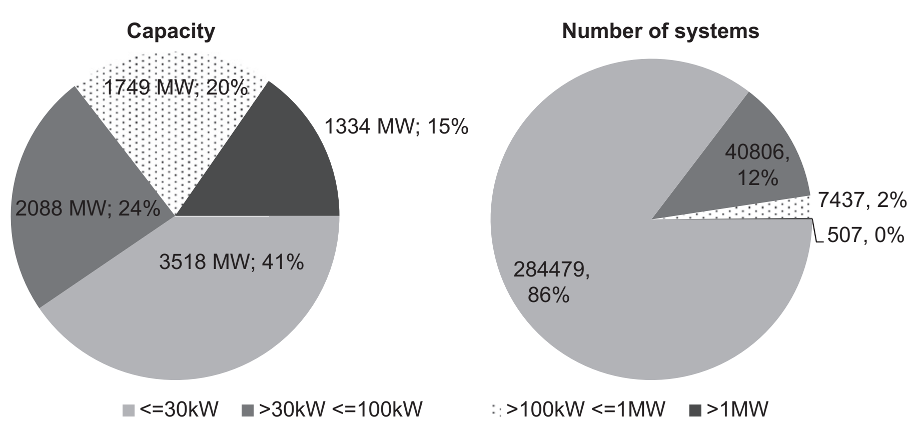

Fig. 9. Germany's distribution of PV installed capacity (MW) and the number of systems by system size (January 2009–August 2010) [60].

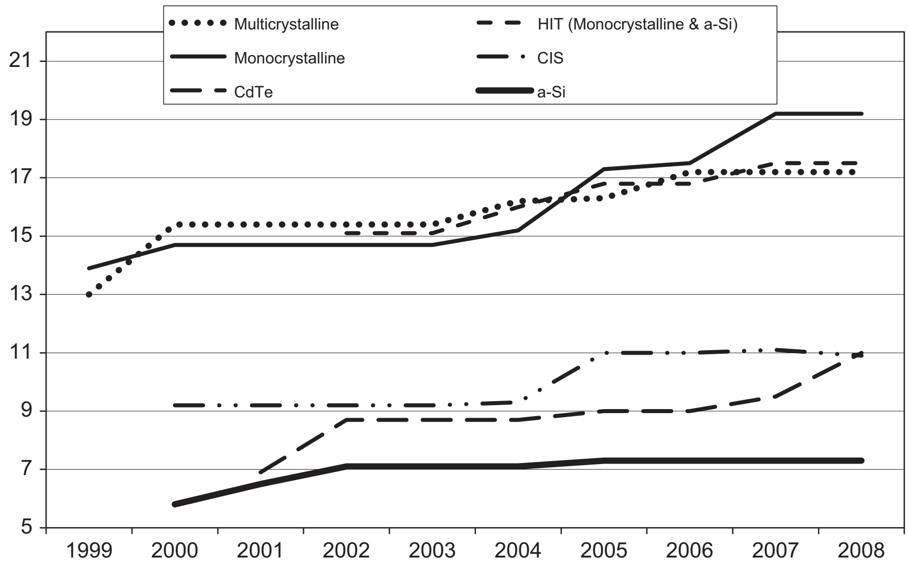

Fig. 10. Trends in solar PV module efficiencies in commercial applications over 1999–2008 [33].

committed for deployment and is estimated to be as less as about one-third of the total required RD&D budget [67].

5. Conclusions

Given the ongoing economic turmoil and scarce ratepayer and taxpayer resources available for solar power, it is important for governments to implement an optimal mix of policies that are effective in balancing national objectives with achieving the long term objective of making solar power competitive with other renewable energy options and subsequently conventional generation.

Although learning-by-doing and economies-of-scale in terms of global PV demand during the 2000s had a role in the reduction in cost of solar power, they may not have delivered cost reductions commensurate with the subsidies provided. RD&D, both incremental and breakthrough can substantially reduce the cost of solar power. However, resources spent on deployment of solar are comparatively an order of magnitude higher than those spent on RD&D. Further, the industry is likely to under-invest in breakthrough RD&D and next generation solar technologies, both due to the high capital requirement and spillover effects that may not let them take total advantage of their RD&D investments. Hence, it is critical for governments to provide adequate investment in basic research and innovation. National efforts and international collaboration on solar energy RD&D need to be expanded based on a systematic assessment of RD&D gaps and funding needs.

Given the various limitations of pull policies in achieving key objectives such as clean energy, energy security, economic development, and others; solar deployment can be done in a more strategic way than is currently being considered in most countries. While smaller PV installations such as rooftop PV in sub-optimal locations are promoted mainly to garner environmental and political support, it is important for policy makers to assess further opportunities for solar deployment in optimal locations. For developing countries like India with large populations without access to electricity, decentralized PV systems present a viable option for providing access to clean lighting and electricity. Opportunities need to be explored to maximize solar electricity generation, thus reducing costs without losing public support.

While the examples of China and Taiwan illustrate that significant deployment support is not essential to develop a strong domestic industry, trade disputes are expected to occur, especially in the present economic slowdown. Hence, for long-term sustainability of the solar sector, it is important for countries to balance pull policies (considering the paying capacity of their consumers) along with push policies, so that the burden of providing a market for solar power is not borne by just a handful of nations.

Various governments have enforced domestic content mandate to prevent domestic subsidies from flowing towards imports. For example, India and Canada (Province of Ontario) have mandated domestic content in their solar programs, while the US is enforcing similar mandates for solar projects funded under the American Recovery and Reinvestment Act. Although from a national perspective, the domestic content mandate seems justified, it prevents countries from utilizing each other's comparative advantages. A transparent assessment of these comparative advantages along with unfair incentives from countries for encouraging exports needs to be undertaken for informed policy choices across countries that would benefit the entire solar industry.

Solar power has become an important and critical renewable energy generation option. It is important for policy makers to optimally design their solar policies by balancing national objectives and paying capacity with the global objective of solar power cost reduction in order to realize its full potential.

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